

Triboelectric charging behavior of wood particles during pellet handling processes



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ABSTRACT

Electrostatic charges accumulated on wood particles through triboelectrification during their transportation and handling processes can cause hazardous electrical discharge which may further trigger dust explosion. In this work, tribo-charging behavior of different kinds of wood particles was investigated by a vibrating plate charging method. It was found that reduction in the work function difference between contact bodies might contribute to the reduction of tribo-charge generation, while the reduction of electrical resistivity of wood pellets could effectively accelerate the charge dissipation. As the particle size decreases, accumulated charges increase significantly. In contrast, higher moisture content of wood particles leads to lower charge accumulation due to an accelerated charge dissipation rate. Tribo-charging behaviors of white pellets, torrefied pellet, steam treated pellets and dark pellets have also been investigated. Compared to the white pellets, they all have shown a reduction on charge accumulation to some extent. However, results suggested that all of them have nearly equivalent tribo-charge density as coal and wheat grains used as references in this study.

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1. Introduction

Climate changes associated with the release of greenhouse gases to atmosphere from the combustion of fossil-fuels have called for the development of renewable, environment friendly and sustainable energy sources. As an abundant and renewable energy source, wood and agricultural residues are considered to be of great potential for replacing the solids fossil fuels.

Wood pellets are made from densification of bulky biomass residues. The densification process reduces the volume of raw biomass to provide a significantly higher energy density per unit volume, thus improving the efficiency of transportation, handling, and storage. Wood pellets have been widely used to substitute thermal coal in large power plants and district heating systems, as well as for home heating, especially in Europe. Canada's endowed forest resources make it becoming a major exporter of high quality wood products to U.S. and wood pellets to European countries. Given that wood pellet mills are located inland, pellets are usually transported by trains between pellet mills and seaports. After a period of storage, they are then loaded into the large ocean vessels in volumes of 7000–20,000 metric tonnes, shipped to destinations

in great distance. During the entire supply chain, numerous handlings are involved within which the risk of dust explosion has become a safety issue in the past 10 years. Several incidents during wood pellets handling in various plants were reported¹, which were speculated to be related with electrostatic-induced dust explosion or self-heating caused spontaneous combustion. In the powder-handling operation, electrostatic charges are always present such as in transporting coal (Nifuku, Ishikawa, & Sasaki, 1989), malt grain (Nifuku & Enomoto, 2001), wood dust (Calle, Klab, Thomas, Perrin, & Dufaud, 2005), and other powders handling

¹ On December 1st 2008, an explosion occurred at Atikokan power generation station (one of Ontario Power Generation's major coal-fired power station) while staffs were preparing for an all wood pellet test burn. Nobody was injured in this accident but the factory was seriously damaged (Source: <http://www.opg.com/news/releases/Atikokan.pdf>). In August 2009, another massive dust explosion occurred at a wood pellet production facility near Farmington, Maine, U.S. The pellet mill is owned by Geneva Wood Fuels LLC. A huge fireball was noticed by workers and the sound of explosion could be heard from about 10 miles away. No human injuries but the factory were damaged with an estimated loss of \$8 million (Source: <http://www.dailybulldog.com/db/features/pellet-mill-damaged-in-massive-explosion/>). In December 2010, a dust explosion blew out a sheet metal wall at the Pacific BioEnergy plant in Prince George, BC, Canada, injuring no one but temporarily knocking production of wood pellets out of commission (Source: <http://news.nationalpost.com/2012/04/28/fatal-sawdust-blast-in-b-c-comes-after-five-explosions-at-similar-plants-since-2009/>).

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industries (Amyotte & Eckhoff, 2010; Mehrani, Bi, & Grace, 2005), and there is always a danger for discharging ignited dust explosion, although there remains much to be investigated on the ignition mechanism (Nifuku & Katoh, 2001). Wood pellets tend to break up during their loading/unloading, pneumatic conveying and storage in deep silos, generating very fine wood dust. At the same time, pellets and fine dust particles can be charged by contacting each other and with the wall surfaces of handling equipment. When the charge level builds up to a certain level, dust explosion can be triggered by sparks or other ignition sources because of the low minimum ignition energy level of wood particles (Melin, 2012). In the current supply chain, pellets may be loaded, unloaded and conveyed several times before being fed into the combustor, generating electrostatically charged dust and creating safety concerns. Melin (2012) reported that the minimum ignition energy of wood particles was lower than that for coal particles. However, to the best of our knowledge, charging behaviors of wood pellets and dusts generated during handling and storage have not been reported in the literature. Therefore, the objective of the present study is to investigate charging behavior of different types of wood pellets and wood dusts in order to understand the dust explosion potential of pellets during their handling and transportation by comparing with two widely transported materials: coal and grain particles.

2. Experimental section

2.1. Test samples

Several types of wood pellets and two reference particles were used in this study. White pellets (WP, made from fibers) were obtained from Premium Pellet Ltd. Torrefied pellets (TP), steam treated pellets (STP), and dark pellets (DP made from wood barks) were obtained from the UBC Biomass and Bioenergy Research Group. The coal sample was obtained from the Mining Engineering Department of UBC, and the wheat grain samples (large flake oats, Rogers, Canada) were purchased from a local supermarket.

White pellets (WP) are the regular wood pellets produced in BC in large quantity, with a moisture content of about 6%. They are produced from nearly pure sawdust, shelving and wood chips, mostly pine with small portions of spruce and fir. Due to the low bark content in the raw material, it is a high quality pellet with very low ash content (<0.5%) and high ash melting temperature (>1300 °C).

Torrefied wood pellets (TWP) are also called the 2nd generation wood pellets made from torrefied (or mildly pyrolyzed) wood. Torrefaction can improve biomass quality such as energy density and hydrophobicity, which offers potential solutions to low energy content and low shelf life of regular pellets. Torrefied pellets samples were provided from the UBC Biomass and Bioenergy Research Group, prepared at a torrefaction temperature of 280 °C.

Steam explosion pretreatment is a chemical modification of the lignocellulosic material to improve its durability in terms of mechanical strength and hydrophobicity (Startsev & Salin, 2000). Steam exploded sawdust particles used in this work were treated at 220 °C with saturated steam at 250 psig over 10 min.

Dark pellets (DP) are made from woody materials that contain majority of wood bark. Because of the high mineral content in the bark, dark pellets used in this project have an average ash content of 3.5% by weight.

Coal and wheat grains were chosen as the references for comparison since they are widely transported and handled commodities and well-studied on their dust generation and explosion potentials. The charging behavior of these two reference particles

Table 1

Prepared white pellet samples with different size distributions.

Groups	Particle sizes μm
A	500–595
B	425–500
C	355–425
D	212–355
E	106–212

enables us to compare the tribo-charging behavior of wood pellets so as to assess the potential for dust explosion.

2.2. Samples preparation

Selected wood pellets were crushed into different sizes, which were then hand sieved into different size ranges, by using US standard brass sieves (Dual MFG Co., USA). As shown in Table 1, white pellets were separated into test samples of different size ranges, while other test samples were prepared in one size range of 212–355 μm only. Prepared samples were stored in sealed plastic containers to keep their moisture contents stable.

The particle densities of test samples were determined from three discrete measurements on each test sample by an analytical balance (Sargent Welch, Model SWW400D, Buffalo, NY), and a multipycnometer (Quantachrome, Model MVP-6DC, Boynton Beach, FL).

The moisture contents of samples were determined by oven drying at 103 °C over 24 h using a Thermo Precision Oven (Thermo-Scientific, USA). All moisture contents reported in this work were on a dry basis.

Basic physical properties of test samples are provided in Table 2. Moisture contents of tested materials are also listed in this table except those samples prepared to examine the effect of moisture content.

2.3. Apparatus & procedure

The experimental apparatus is illustrated in Fig. 1.

As shown in Fig. 1, a vibratory feeder with a stainless steel tray (Eriez 15A, Eriez, USA) was utilized as the tribo-charger. Rubber discs on the inside of the vibratory attachment separate the tray from the vibratory base, at their point of contact, to minimize electrical discharges of the vibratory tray through the base. A Faraday cup, which consists of two brass cups isolated from each other by a Teflon spacer, was used. The inner cup is connected to an electrometer (Keithley Model 6514, Cleveland, OH), and the outer cup is grounded. In this work, each test was successively repeated by eight times and the average charge of each tested sample was obtained by averaging the eight repeated runs with the spreading indicated by the standard deviation.

Table 2

Physical properties of tested samples.

	Particle density (Kg/m^3)	Moisture content (%wt on dry basis)
White pellet (WP)	1426	6.32
Torrefied pellet (TP)	1420	3.02
Steam treated pellet (STP)	1428	3.78
Dark pellet	1414	7.93
Coal	2336	1.47
Wheat grain (WG)	1409	9.58

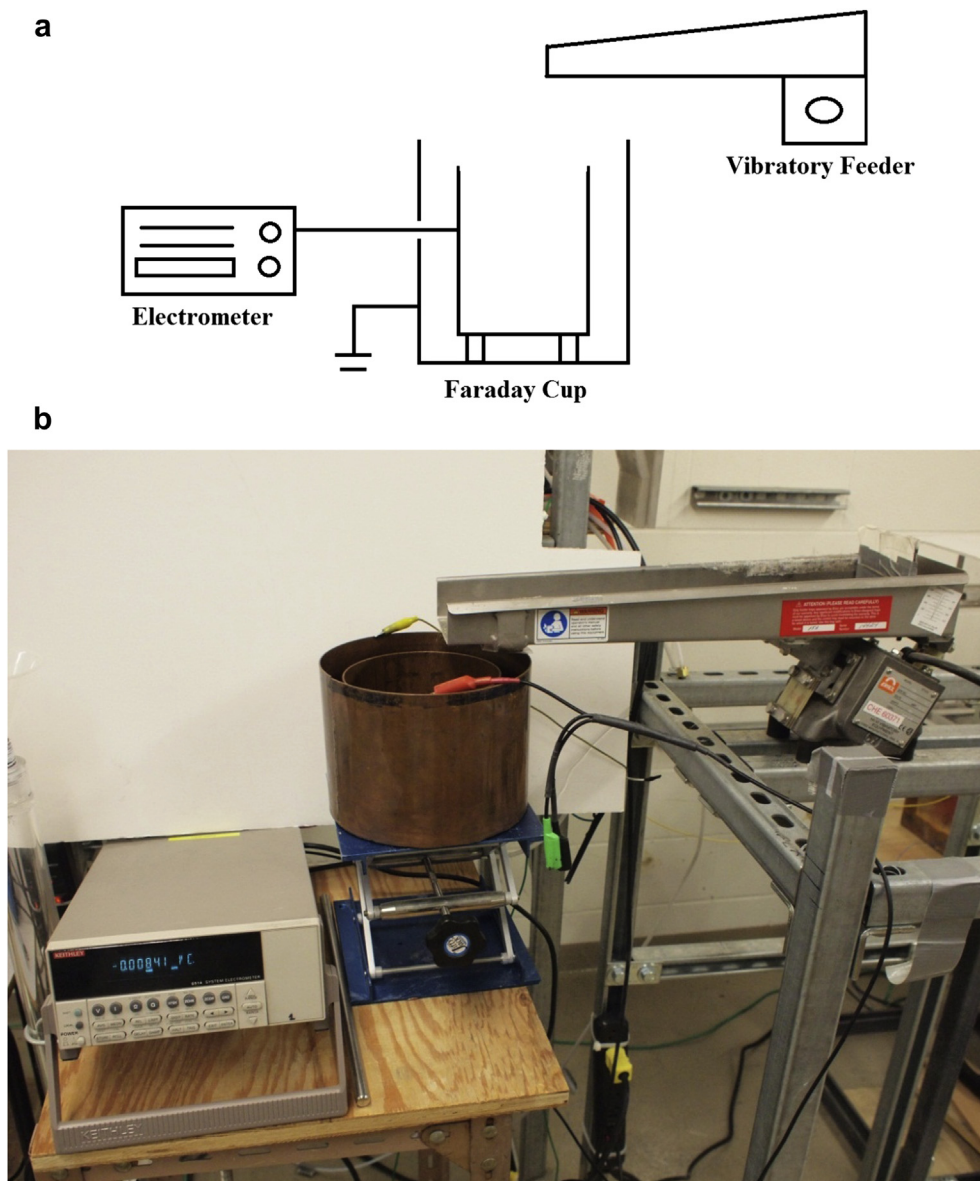


Fig. 1. (a) Schematic and (b) a photo of the tribo-charging testing apparatus.

3. Results and discussion

3.1. Effect of particle size

Fig. 2 shows the charge to mass ratio and the charge to particle surface area ratio for white pellet particles with different particle sizes. The mean particle size of each tested sample was estimated by assuming a normal size distribution. The particles of 212–355 μm show the highest specific charge density of $-24.77 \mu\text{C/kg}$, while particles with the largest size (500–595 μm) have the lowest specific charge density of $-9.40 \mu\text{C/kg}$. The charge to surface area ratio remains in a range of -0.87 to $-1.67 \mu\text{C/m}^2$, which is less sensitive to the particle size. Good reproducibility is achieved, as evidenced by the standard deviations calculated from 8 repeated runs for each tested sample. According to the tribo-electrification theory, the charge generation is mainly governed by the work function difference, the total contact surface area between the particles and the dropping plate. The total contact surface area of a given bulk volume of particles is proportional to the square of

particle diameter. Therefore, the finer the particle size is, the larger the total contact surface area will be. Thus, particles with smaller sizes may acquire more charges per unit mass in the tribo-charging process. This trend is supported by the results shown in Fig. 2, except the result of the finest particles (106–212 μm) which indicate a lower specific charge acquired that is opposite to what is expected. An experimental observation revealed that very fine particles used in the current study tended to agglomerate into large lumps, which might no longer represent the performance of individual particles. Furthermore, it was observed experimentally that these very fine particles had a higher probability to stick onto the vibration plate to form a thin dust layer, which reduced the probability of particle-to-plate contact.

The transferred charge Δq_c caused by collision between particles and wall surfaces can be represented by (Matsusaka, Ghadiri, & Masuda, 2000)

$$\Delta q = k_c CV \quad (1)$$

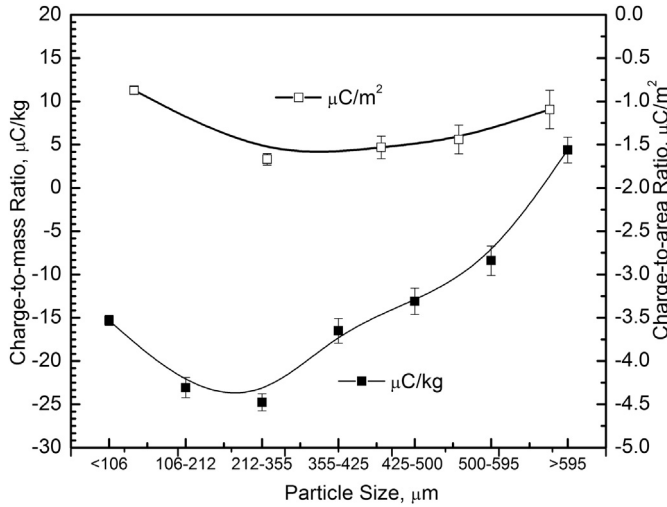


Fig. 2. Effect of particle size on charging behavior for white pellet samples.

where k_c is the charging efficiency and V is the total potential difference. C is the capacitance between the contact bodies, which is given by the following equation (Matsusaka et al., 2000):

$$C = \frac{\epsilon \epsilon_0 S}{z_0} \quad (2)$$

where ϵ is the relative permittivity of air, ϵ_0 is the permittivity of vacuum, S is the contact area and z_0 is the gap between the contact bodies. The total potential difference V between the contact bodies is comprised of two parts: (a) the contact potential difference V_c based on work functions difference and (b) V_e arising from image charge. These are related as follows (Matsusaka et al., 2000):

$$V = V_c - V_e \quad (3)$$

The contact potential difference V_c is given by

$$V_c = \frac{(\phi_p - \phi_w)}{e} \quad (4)$$

where ϕ_p is the effective work function of particle and ϕ_w is the work function of metal wall. And e is the elementary charge.

The potential difference arising from image charge V_e is given by Matsusaka et al. (2000)

$$V_e = k_0 q \quad (5)$$

where k_0 is a constant and q is the initial charge on the particle before impact.

Combining equations (1)–(5), the transferred charge Δq_c caused by impact can be expressed by

$$\Delta q = \frac{k_c \epsilon \epsilon_0 S}{z_0} \left(\frac{(\phi_p - \phi_w)}{e} - k_0 q \right) \quad (6)$$

When wood particles of little initial charge come into contact with the metal plate, the total contact surface area (S) and the difference of work functions of two contact bodies are the most important factors to influence the charge generation on particles. According to equation (6), the particle–particle contact may generate less charge than particle–wall contact because the work function difference between particles is much smaller than that between particles and the steel plate. Similar results showing decreased saturation charges for the shielded particles were also

reported and discussed in the previous research (Nader, Castle, & Adamiak, 2010).

In a well-known triboelectric series table, wood is only one level lower than steel (Adams, 1987), suggesting that wood particles have the tendency to be charged negatively when they contact with the steel plate (gain electrons). This appears to be consistent with the measured negative polarity of white pellet particles as indicated in Fig. 2 in this work.

3.2. Effect of moisture content

Fig. 3 shows the effect of moisture content on specific charges of white pellet particles in the size range of 212–355 μm after contacting with the steel vibratory tray. The moisture content is defined as mass percentage of water in tested pellet particles, in %. The results follow a trend that the specific charge density decreases while the moisture content increases, except that the dry particles have a slightly lower specific charge density than the particles with 3% moisture content. According to equation (6), the charge generation rates between the metal tray and the tested samples of same material are expected to remain the same. However, surface electrical conductivity of particles increases with increasing moisture content due to the high conductivity of moisture on the particle surface. Higher surface electrical conductivity may help particles dissipate charges faster (Cross, 1987).

It was also reported in the literature that the electrical resistivity of wood varies greatly with its moisture content, especially below the fiber saturation point. As the moisture content of wood increases from near zero to fiber saturation, electrical resistivity decreases from about 10^{14} – 10^{16} Ω m for oven dry wood to 10^3 – 10^4 Ω m for wood at fiber saturation (Glass & Zelinka, 2010).

As the moisture content further increases from fiber saturation to complete saturation of the wood structure, the increase in conductivity is smaller and erratic. As presented in Fig. 3, the specific charge density increases significantly when the moisture content of particles decreases from 9% to 6%. The gradient became less steep when the moisture content was greater than 9%. On the other hand, the dry particles in this group presented a lower specific charge (-22.2 μC/kg) than expected. It is likely due to their high tendency to agglomerate and stick onto the vibratory tray, as observed experimentally, preventing the direct particle–wall

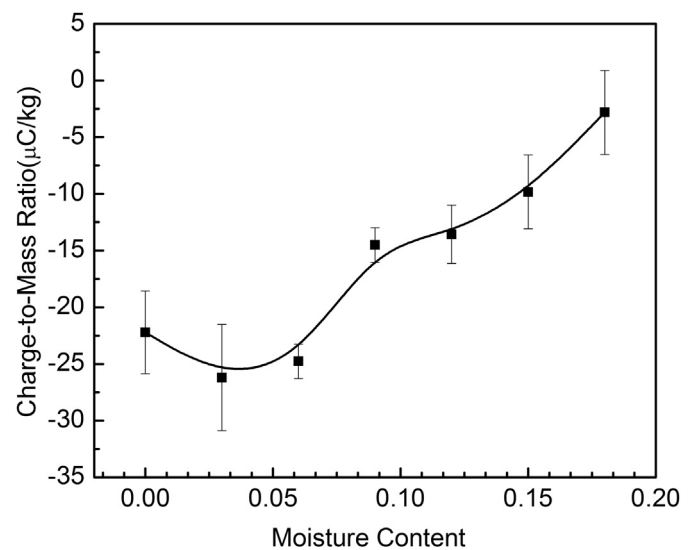


Fig. 3. Specific charge of white pellet particles (212–355 μm) at different moisture content (mass fraction).

contact which might reduce the charge generation. The moisture content of 18%–20% is the maximum value which can be achieved experimentally in the current work. Beyond this range, water is vaporized very quickly once taken out from the humidity chamber. The standard deviation of the specific charges was higher for particles of very low or very high moisture content. This is believed to be due to the quick moisture adsorption and evaporation during the tests.

Adding moisture to particles is a well-known method to reduce electrostatic charges buildup in particle transport lines. However, moisture content has to be controlled around 8–10% in the pelletization process for making strong pellets with a final moisture contents around 6%. Too much moisture makes the feedstock slip through the dies easily during compaction, and thereby reducing the pellet quality including hardness and durability. In most cases, the durability of the densified pellets increases with increasing the feed material moisture content until reaching a peak value. In addition, higher moisture content in the pellet will reduce the net energy density of pellets and shorten the shelf life of pellets. Therefore, the optimized moisture content should be carefully controlled even if it may benefit charge elimination.

3.3. Effect of contact surface

The charge-to-mass ratio measured using different vibratory tray surface materials is shown in Fig. 4. It is seen that the charge-to-mass ratio was doubled when steel surface was used, compared to pine wood surface and 3M Scotch[®] taped surface. The pine wood sheet has a work function very close to wood pellets because of their similar compositions. When the work function difference decreases, less electrostatic charges would be generated from the contact of the two materials. As a result, the specific charge transferred from the particles to the steel surface is expected to be higher than the wood surface.

Negative charge polarity of tested particles was also observed from contact of particles with the pine wood sheet. The polarity was determined by the actual effective work functions of tested particles and the pine wood sheet, which are difficult to be estimated or measured due to their amorphous compositions. However, the experimental results indicated that the tested particles

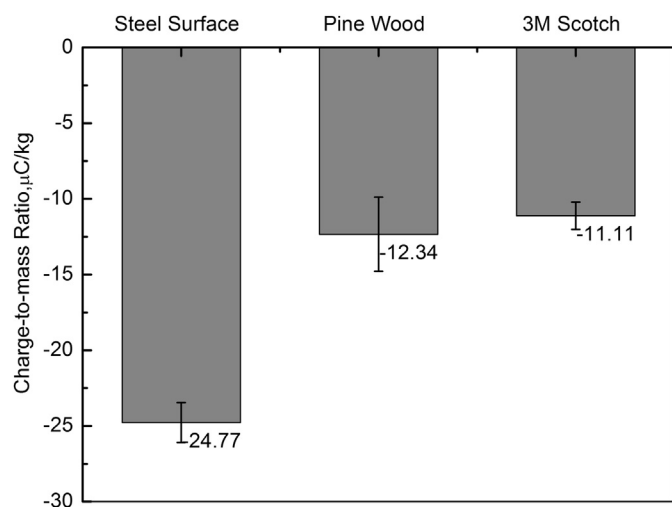


Fig. 4. Specific charge of white pellet particles after contact with different vibratory surfaces.

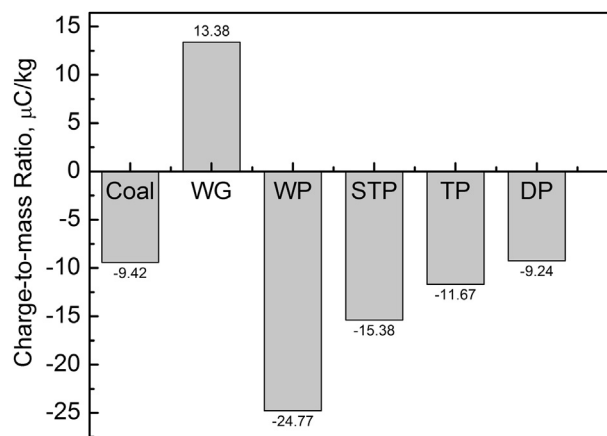


Fig. 5. Charge to mass ratios for different types of particles (WG: wheat grain; WP: white pellet; STP: steam treated pellet; TP: torrefied pellets; DP: dark pellet).

should have a higher effective work function than the pine wood plate used in this study.

The results on 3M removable Scotch[®] taped surface are quite similar to the wood surface, with lower charges generated from contacting pellet particles with the Scotch[®] taped surface. The Scotch tape or cello tape has been employed to coat the inner surface of fluidized bed columns to minimize charge generation (Grace & Baeyens, 1986). The current experimental results appear to support the effectiveness of such a practice, although the underlying fundamental mechanism is still unclear.

In order to effectively prevent charge generation and accumulation on wood pellets, it is highly recommended to use woody surfaces in the equipment and conveyors during loading, unloading and conveying operation. Containers or handling equipments made of or coated with some plastic materials may also be effective in charge reduction which, however, requires further investigation.

3.4. Performance of different particulate materials

The charge to mass ratio and charge to particle surface area ratio for all particles studied in this work are presented in Figs. 5 and 6, respectively, using particles in the same size range of 212–355 μm.

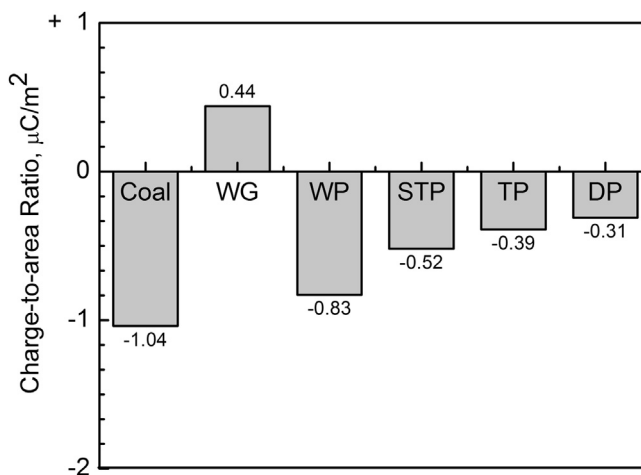


Fig. 6. Charge to surface area ratios for different types of particles (WG: wheat grain; WP: white pellet; STP: steam treated pellet; TP: torrefied pellets; DP: dark pellet).

The white pellet particles have the highest specific charge as well as charge to particle surface area ratio among all tested wood pellet particles while all other test particles have a similar magnitude of charge densities.

3.4.1. Coal & wheat grain

Coal and wheat grains are chosen for tests because they are well studied on dust generation and explosion potentials (Nifuku & Enomoto, 2001; Nifuku et al., 1989). It can be seen that coal particles have a lower specific charge density compared to white pellet particles. The lower specific charge of coal particles can be related to their high surface conductivity than white pellets. It has been reported that the electrical resistivity of coal generally falls into a range of 10^2 – 10^5 Ω m, mainly depending on the types of coal (Speight, 2005). Compared to the typical wood electrical resistivity of around 10^8 Ω m, coal particles have a much higher ability to dissipate charges generated from contact with the steel vibratory tray.

The results indicate that wheat grain particles are always charged positively, although the magnitude of the charge density is only 50% of the white pellet particles. The actual charge mechanism for wheat grain in contact with steel plate is not clear due to the lack of data on both its work function and electrical conductivity.

Based on the results shown above, it can be concluded that the white pellet particles have a higher charge accumulation potential than coal and wheat flour particles. According to the dust explosion hazard rating index issued by the Department of Labour of New Zealand in 1985, wheat and wood are listed in the same hazard level of “moderate to strong” and coal is listed in the hazard level of “moderate to severe” (1985). The current study showed that dusts from dry white pellets tend to be charged more easily, leading to higher hazard than coal powders.

3.4.2. Steam treated pellets (STP)

Comparing to white pellets, particles from steam treated pellets have lower specific charge density and charge to surface area ratio, -15.38 C/kg and -0.52 C/m², respectively. During the steam explosion treatment, high molecular weight lignin is cleaved to low molecular weight lignin which melts, redistributes and condenses into larger molten bodies that migrate within and out of the cell wall, which can redeposit on the surface of plant cell walls. A thermal degradation of hemicellulose also occurs during the steam treatment, which may contribute to the increase in the percentages of lignin and cellulose. From the triboelectric series (Adams, 1987), cellulose is located in the positive side of steel, which means that cellulose has a tendency to lose electrons when in contact with steel to gain a positive charge polarity. Therefore the increased percentage of cellulose may also increase the probability to lose electrons, leading to the decrease in the total negative charge density. In addition, some literatures indicate that lignin is a material between insulators and semiconductors (Chupka & Rykova, 1983). Therefore, it can be inferred that the electrical resistivity of particles may decrease as the percentage of lignin is increased, which allows surface charges to dissipate faster and further lower the specific charge density of particles.

In contrast, the hemicellulose degradation during steam treatment may increase the hydrophobicity of the wood pellet by eliminating the water-soluble OH groups which attract water and form gels. The lower moisture content of steam treated pellet (3.78%), compared to 6.32% for white pellets may lead to a higher level of charge accumulation.

3.4.3. Torrefied pellets (TP)

Compared to the white pellet particles, a nearly 53% decrease on specific charge density is observed for torrefied pellet particles.

During the torrefaction, low molecular volatiles are removed from the biomass, leading to a decrease in mass and an increase in energy density. The torrefied biomass has a lower oxygen/carbon ratio and higher carbon content compared to the raw biomass (Bergman, Boersma, Zwart, & Kiel, 2005). The electrical resistivity of carbon is about 3.5 Ω m (Cutnell & Johnson, 1998), which is much lower than wood. The increase of carbon content in torrefied wood will increase the surface electrical conductivity, and thus lower the specific charge accumulation. On the other hand, torrefied wood pellets have a higher hydrophobicity that will extend their shelf life. The decrease in moisture content, however, may counteract the higher surface electrical conductivity of torrefied particles. Based on the observed reduction in charge buildup in torrefied particles from this study, it appears that the effect of carbon content is more dominant than that of the reduction in moisture content.

3.4.4. Dark pellets (DP)

Among all tested samples, dark pellet particles show the lowest surface charge density, 63% lower than white pellet particles. The same mechanism for torrefied pellets can be applied to explain the low charge density for dark pellets. Ash in wood consists mostly of metal oxides such as Na⁺ (Sodium), K⁺ (Potassium) and Ca²⁺ (Calcium). Wood bark contains 10–20 times the ash of white wood. The higher metal contents in bark particles result in higher surface electrical conductivity, and thus lower charge accumulation.

Although the tested steam treated particles, torrefied particles and dark pellet particles have all shown lower surface charge accumulations than white pellet particles, their specific charge densities are still in the similar range as coal and flour particles. It means that the dust explosion risk of these pellets during handling and transportation cannot be ignored, and cautions should also be exercised in practice.

3.5. Implications in wood pellet handling

As stated earlier, wood pellets tend to break up during various their handling operation, resulting in very fine wood dust. Mina-Boac, Maghirang, and Casada (2006) showed that the percentage of broken pellets (<5.60 mm) increased from an initial value of 17.5%–50.2% after repeated handling (eight transfers) of 22.6 tonnes of feed pellets. The average mass of dust removed in each transfer is 0.069% of the mass of pellets. Consequently, preventing the generation of fine particles from minimizing pellet breakage during the handling and transportation is extremely important in avoiding the buildup of electrostatic charges. Possible approaches include the improvement of the durability of wood pellets and minimization of damage caused by pellet handling equipments.

Durability of wood pellets is influenced by several factors, including wood species, particle size, moisture content, lignin content, preconditioning of raw materials and densification equipments used in pelletization (Kaliyan & Morey, 2009). Based on previous studies, the durability of wood pellets can be improved by optimizing manufacturing process and raw material selections. For instance, the maximum durability of 96.7% can be reached when moisture content of sawdust is at a level of 8.62% (Colley, Fasina, Bransby, & Lee, 2006). In addition, increasing lignin content of the raw wood material is proven to increase the durability of wood pellets. The degree of densification of biomass also affects the durability in a number of ways, including the external load, wedging forces and bonding agent (Mani, Tabil, & Sokhansanj, 2003).

The high impact handling of wood pellets is another major cause of pellet breakage. For example, the silo or ocean vessel container

filling from conveyors may break pellets if the pellets are dropped from too high an elevation. The previous study showed that pellet breakage almost linearly correlated with the drop height (Oveisi-Fordiie, 2011). The percentage of dust increased significantly with repeated drops. The amount of dusts and fine particles generated also depended on the bedding material. In general, a hard surface such as concrete has a greater impact on pellets compared to the soft bedding (Oveisi-Fordiie, 2011). Therefore, all conveying systems that encourage high impacts or rubbing, wedging or grinding actions should be avoided, including chain conveyors and screw conveyor feeders. The least damaging method for handling wood pellets is to carry them on belt conveyors with rubber surfaces. A properly designed conveyor is also required to minimize the impact points. Additionally, the dropping height should be controlled carefully. For the land transportation such as by train, the standard gondola cars that require emptying on a roll-over dumper should be avoided due to the pellet damage associated with the frequent material impacts. Bottom-discharge gondola cars are suitable. In-situ dust collectors, such as baghouses, might be essential with air ventilation in minimizing dust buildup in enclosed environment.

4. Conclusions and recommendations

In this work, it was found that the specific charge density of tested white pellet articles increased significantly with the reduction in the particle size. However, the insignificant variations of charge to surface area ratios suggest that the charges are primarily accumulated on the outer surface of particles. Very fine particles tend to agglomerate and stick to the dropping plate, reducing charge generation by reducing particle-wall contacts. Higher moisture content in wood pellets leads to a higher charge dissipation rate and helps to reduce charge buildup. However, the optimized moisture content should be carefully controlled to maintain wood pellet energy density and shelf life.

The charge accumulation on particles can be reduced through covering the vibratory tray by the material made of similar ingredient as contact particles. Charge reduction by covering the vibratory tray with 3M removable Scotch® tape is also observed experimentally but the actual charge reduction mechanism is still unclear. In practice, it is highly recommended to use woody surfaces or plastics coated surfaces for containers or handling equipments.

Torrefied pellet particles, steam treated pellet particles and dark pellet particles showed lower specific charge density or charge to surface ratio than white pellet particles. However, all of them have a similar tribo-charge density as coal and wheat grains. Therefore, the same level of caution as coal and grain needs to be exercised in handling those pellets.

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